

Measurement of the CKM angle γ at LHCb

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1 The CKM angle γ

The Standard Model (SM) describes all known fundamental particles and their interactions, excluding gravity. It has survived rigorous experimentation over four decades. However some observations, like baryon matter asymmetry in the universe, remain inadequately explained. This asymmetry requires breaking of Charge-Parity (CP) symmetry [1], among other requirements.

In 1973, M. Kobayashi, and T. Maskawa [2], proposed the Kobayashi-Maskawa mechanism, now known as the Cabibbo-Kobayashi-Maskawa (CKM) formalism. In this formalism, the CKM matrix quantifies the couplings between quarks of different flavour. It is a transformation between quark mass and flavour eigenstates:

$$\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} = \underbrace{\begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}}_{V_{\text{CKM}}} \begin{bmatrix} d \\ s \\ b \end{bmatrix}. \quad (1)$$

Presence of complex phases in some of the couplings lead to CP violation in particle decays. Expressing the CKM matrix using the Wolfenstein parametrisation [3],

$$V_{\text{CKM}} = \begin{bmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{bmatrix} + \mathcal{O}(\lambda^5), \quad (2)$$

provides a description of the CP violating particle decays involving the complex phases on V_{ub} , V_{td} , and V_{ts} .

Imposing unitarity conditions allows us to represent the CKM matrix by six triangles on the complex plane. Precise determination of the CKM triangle is needed to scrutinise the consistency of the SM. Although there have been many efforts to measure the triangle before, the angle γ ,

$$\gamma = \arg(-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*), \quad (3)$$

remains poorly determined.

2 The LHCb detector

All analyses discussed here are performed with data recorded with the LHCb detector at CERN. The LHCb detector operates in the busy hadronic environment of the Large Hadron Collider. The design and performance of the detector are discussed in greater detail elsewhere [4]. It operates as a precise momentum spectrometer with a pseudo-rapidity coverage in the forward region, $2 < \eta < 5$, which covers 40% of the beauty production cross-section. It offers excellent track reconstruction and decay vertex resolution making it ideal for studying long-lived particles like B -mesons. LHCb includes two Ring-Imaging Cherenkov (RICH) detectors for particle identification, allowing for powerful discrimination between kaons, pions, and protons. Together with the calorimeters and the muon detector, LHCb provides identification of muons, electrons, and photons. These capabilities are essential to study the fully hadronic decay modes described later.

3 Measuring γ using hadronic *tree* decays

Past γ measurements were done by the BABAR and Belle collaborations using coherent production of charged B -meson decays. In 2012, the Belle collaboration reported a γ value of $(68^{+15}_{-14})^\circ$ [5]. Similarly, the BABAR collaboration reported γ to be $(69^{+17}_{-16})^\circ$ [6].

In this article I will summarise γ measurements at LHCb from tree decays of B -mesons, as opposed to the determination through charmless B -decays with higher order diagrams [7], leading to the world's most precise determination. The measurements can be categorised into two types: decay-time integrated, and decay-time dependent. To gain precision, we statistically combine the different results. I conclude with an outlook on the future of γ measurements.

3.1 CP violation in decay-time integrated $B^\pm \rightarrow Dh^\pm$

There are several well established methods to determine γ from $B^\pm \rightarrow Dh^\pm$ decays, where D stands for an admixture of D^0 and \bar{D}^0 . The methods use asymmetries in decay-time integrated decay amplitudes as one of the observables of interest. I present a selection of such analyses below.

$B^\pm \rightarrow Dh^\pm$ decays can provide powerful methods for γ determination. The amplitude of $B^- \rightarrow D^0 K^-$ is proportional to V_{cb} , whereas $B^- \rightarrow \bar{D}^0 K^-$ is proportional to V_{ub} (see Fig. 1). If the D final state is accessible to both D^0 and \bar{D}^0 , the two decay paths can interfere and one can extract observables sensitive to γ .

So far only D decays where they decay into CP -even eigenstates (e.g. $D \rightarrow K^+ K^-, \pi^+ \pi^-$) [8], or other modes like $D \rightarrow \pi^- K^+$ [9] have been considered. These two methods are named after the initials of the proponents as “GLW”, and “ADS” respectively. For the ADS modes, the $B^- \rightarrow D^0 K^-$ decay is followed by a doubly Cabibbo-suppressed D decay, whereas the suppressed $B^- \rightarrow \bar{D}^0 K^-$ is followed by a favoured D decay mode. This results in comparable amplitudes for both decay paths, leading to larger interference in comparison to GLW modes. A schematic diagram illustrating this effect is shown in Fig. 1.

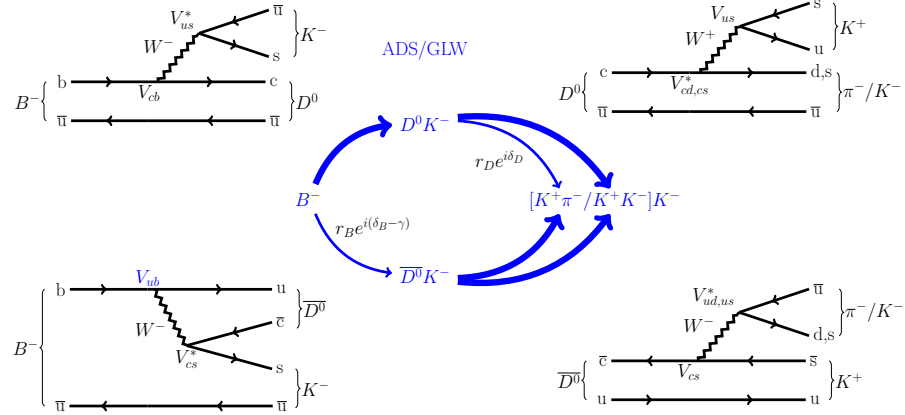


Figure 1: Schematic diagram showing relative amplitude and interference of $B^\pm \rightarrow Dh^\pm$ decays considered by the ADS, and GLW methods.

Notable observables for both of these methods are partial widths ratios and CP asymmetries shown below.

$$R_{CP+} = 1 + r_B^2 + 2r_B \cos \delta_B \cos \gamma \quad (4)$$

$$A_{CP+} = 2r_B \sin \delta_B \sin \gamma / R_{CP+} \quad (5)$$

$$R_{ADS} = r_B^2 + r_D^2 + 2r_B r_D \cos(\delta_B + \delta_D) \cos \gamma \quad (6)$$

$$A_{ADS} = 2r_B r_D \sin(\delta_B + \delta_D) \sin \gamma / R_{ADS} \quad (7)$$

The variables labelled $CP+$ correspond to modes where the D decays to CP -even eigenstates (GLW), and the variables corresponding to the ADS method are labelled ADS . B decay rate ratios are called R , whereas CP asymmetries are called A . The observables in Eqs. (4–7) have been expressed in terms of amplitude ratios (r_B and r_D), strong phase differences (δ_B and δ_D), and the CKM angle γ (see Fig. 1 for an illustration depicting the role of the physics parameters).

The GLW method has the advantage of having larger event statistics, owing to favoured D decay modes, whereas the ADS method can boast large interference due to comparable decay amplitudes. The invariant mass distributions from these measurements are shown in Fig. 2. The top row shows events measured using the GLW method, and events measured with the ADS method are shown below. Analysis of the $B \rightarrow DK$ ADS mode shows evidence of a large negative asymmetry at 4.0σ significance. Similarly the combined $B \rightarrow Dh$ GLW modes show positive asymmetries (4.5σ) [10]. Subsequently, measurements for suppressed ADS modes, where the D undergoes a 4-body decay to $K\pi\pi\pi$ were also performed successfully [11].

Yet another method to extract γ from $B^\pm \rightarrow DK^\pm$ decays, involves the D decaying to a self CP -conjugate state like: $K_S^0 K^+ K^-$ or $K_S^0 \pi^+ \pi^-$ [12], henceforth collectively referred to as $K_S^0 h^+ h^-$. This method is labelled “GGSZ” after the initials of the proponents. The idea is to compare $D \rightarrow K_S^0 h^+ h^-$ final states in the Dalitz plane between $B^+ \rightarrow DK^+$ and

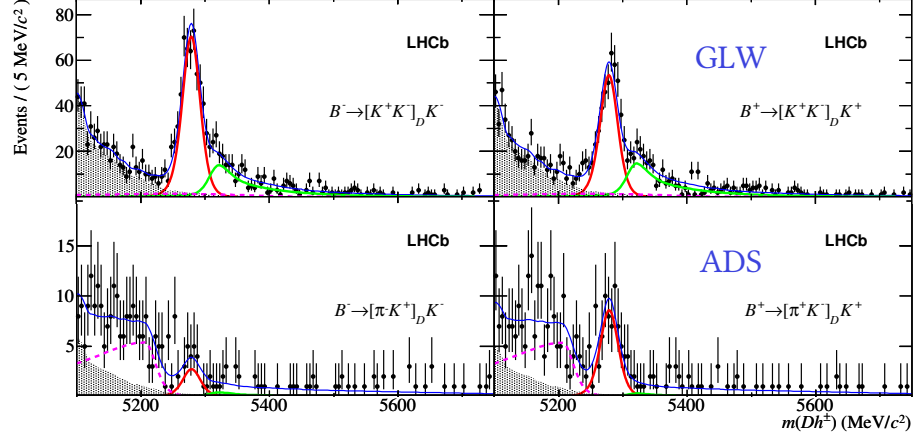


Figure 2: $B^\pm \rightarrow Dh^\pm$ events measured using the GLW, and ADS methods.

$B^- \rightarrow DK^-$ decays. This method requires a good understanding of the variation of strong phase in the Dalitz plane. Which is known from direct measurements of the decay of $D^0\text{-}\bar{D}^0$ entangled pairs from $\psi(3770)$ decays [13], performed by the CLEO-c collaboration. Fitting the Dalitz bin contents, we measure the observables:

$$x_\pm = r_B \cos(\delta_B \pm \gamma), \quad \text{and} \quad y_\pm = r_B \sin(\delta_B \pm \gamma), \quad (8)$$

where x_\pm and y_\pm are Cartesian parameters sensitive to γ . Analysing the complete 3fb^{-1} dataset, we find best fit values for the observables in Eq. (8) are consistent with non-zero. Fig. 3 shows the best fit values and two of the corresponding Dalitz plots [14].

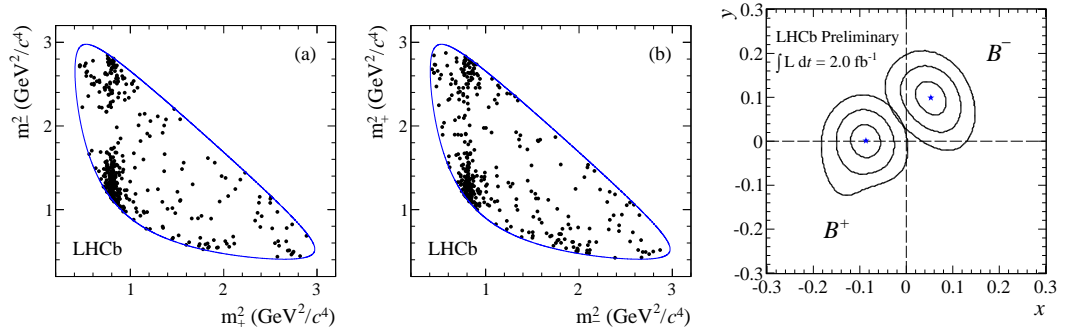


Figure 3: Dalitz plots for $D \rightarrow K_S^0 \pi^+ \pi^-$ separated between B^+ (left) and B^- (middle) decays are shown above. On the Dalitz plane, m_+ stands for the invariant mass constructed from the K_S^0 and the π^+ , and m_- is constructed from the K_S^0 and π^- . Best fit values of (x_\pm, y_\pm) from the GGSZ analysis are shown on the right. Central values are indicated by a star; 1σ , 2σ , and 3σ confidence levels are also shown.

3.2 CP violation in time-dependent $B_s^0 \rightarrow D_s^\mp K^\pm$

$B_s^0 \rightarrow D_s^\mp K^\pm$ decays present an opportunity to measure γ from tree decays by studying the decay-time distribution of the B_s -meson [15]. Both B_s^0 and \bar{B}_s^0 can decay to the two final states: $D_s^- K^+$ and $D_s^+ K^-$. This leads to a superposition of four decay equations, with five CP violation parameters which depend on γ . In this analysis, we first perform a multi-dimensional mass fit to the B_s -mass, D_s -mass, and Kaon particle identification distributions to determine the proportions of different physics contribution in our signal mass window. Subsequently we fit the decay-time distribution and extract the CP observables and find $\gamma = (115_{-43}^{+28})^\circ$, $\delta_{D_s K} = (3_{-20}^{+19})^\circ$, and $r_{D_s K} = 0.53_{-0.16}^{+0.17}$ [16]. Time-dependent asymmetry plots for the two final states are shown in Fig. 4.

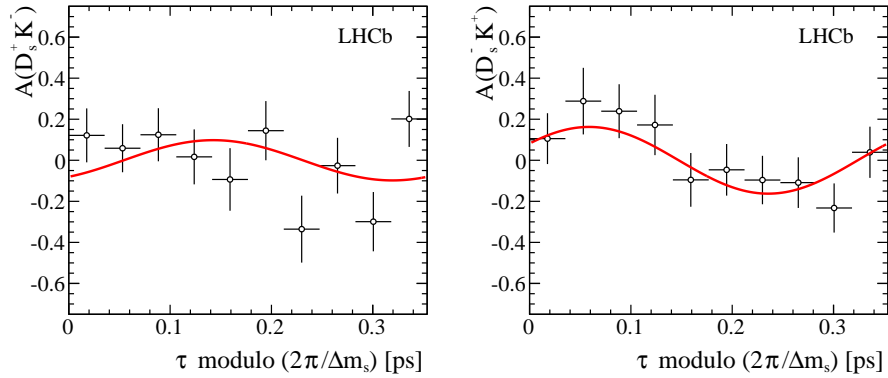


Figure 4: Time-dependent asymmetry for the two final states where the decay-time axis has been remapped to one oscillation period.

4 Combination of γ measurements

We perform a χ^2 combination of all the experimental inputs from the $B^\pm \rightarrow Dh^\pm$ decays (including $B \rightarrow D\pi$). Results from the ADS and GLW analyses with 1fb^{-1} of data, and the GGSZ analysis using 3fb^{-1} of data are combined. Effects of D^0 mixing [17] are taken into account and hadronic parameters for the D^0 from the CLEO collaboration [18] are used. We find $\gamma = (67 \pm 12)^\circ$ at 68% C.L [19].

The result presented above was the world's most precise measurement of the angle γ at the time of the conference. However, since then an updated result of $\gamma = (73_{-10}^{+9})^\circ$ was presented by the LHCb collaboration [20]. The new result includes other B decay modes, such as, $B \rightarrow DK^*$ [21], and new D decay modes for existing channels, like $B \rightarrow Dh$, $D \rightarrow K_S^0 K\pi$ [22]. These two analyses along with the updated GGSZ analysis [23] use the complete 3fb^{-1} dataset. The updated combination also includes the decay time-dependent measurement of $B_s^0 \rightarrow D_s^\mp K^\pm$ decays. In the long run, precision of γ measurement at LHCb is expected to improve significantly. Table 1 provides a brief summary.

Recently results from a previously unexplored analysis, $\Lambda_b^0 \rightarrow D^0 ph^-$ [25], with a promis-

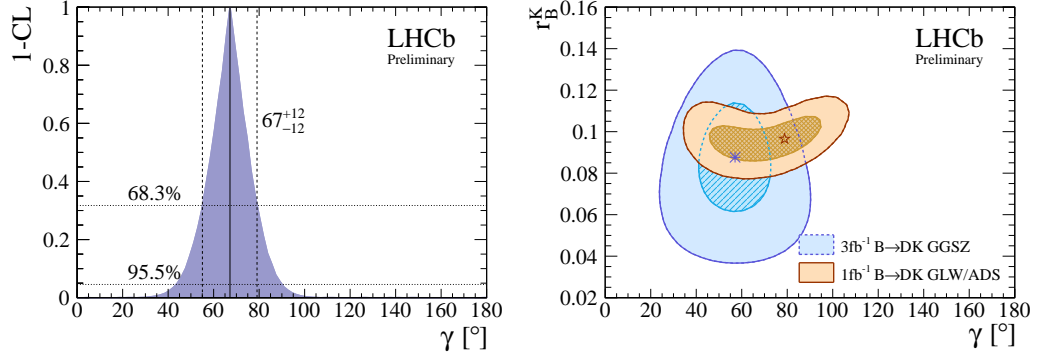


Figure 5: Left: 1-CL distribution for γ for $B^+ \rightarrow DK^\pm$ decays. Best fit values are shown with uncertainties corresponding to 68.3% CL intervals. Right: Profile likelihood contour plot for γ . Contours corresponding to 1fb^{-1} (orange) and 3fb^{-1} (blue) data are shown separately.

Table 1: Expected sensitivity for γ measurements at LHCb from charged B decays, and time-dependent measurements [24].

	Run II	Upgrade
$\gamma(B \rightarrow DK)$	4°	0.9°
$\gamma(B_s \rightarrow D_s K)$	11°	2°

ing possibility to contribute to γ measurement [26] was also reported by LHCb. To conclude, precision of the measurement of angle γ has been improving steadily. LHCb is expected to make significant contribution towards this goal over the coming years.

References

- [1] A. D. Sakharov, Pisma Zh. Eksp. Teor. Fiz. **5** (1967) 32
- [2] M. Kobayashi and T. Maskawa, Prog. Theor. Phys. **49** (1973) 652.
- [3] L. Wolfenstein, Phys. Rev. Lett. **51** (1983) 1945.
- [4] A. A. Alves, Jr. *et al.*, [LHCb coll.], JINST **3** (2008) S08005; R. Aaij *et al.*, [LHCb coll.], arXiv:1408.1251 [hep-ex].
- [5] K. Trabelsi [Belle coll.], arXiv:1301.2033 [hep-ex].
- [6] J. P. Lees *et al.* [BaBar coll.], Phys. Rev. D **87** (2013) 5, 052015.
- [7] R. Aaij *et al.*, [LHCb coll.], arXiv:1408.4368 [hep-ex].
- [8] M. Gronau and D. London, Phys. Lett. B **253** (1991) 483; M. Gronau and D. Wyler, Phys. Lett. B **265** (1991) 172.

- [9] D. Atwood, I. Dunietz and A. Soni, Phys. Rev. Lett. **78** (1997) 3257; D. Atwood, I. Dunietz and A. Soni, Phys. Rev. D **63** (2001) 036005.
- [10] R. Aaij *et al.*, [LHCb coll.], Phys. Lett. B **712** (2012) 203 [Erratum Phys. Lett. B **713** (2012) 351].
- [11] R. Aaij *et al.*, [LHCb coll.], Phys. Lett. B **723** (2013) 44.
- [12] A. Giri, Y. Grossman, A. Soffer and J. Zupan, Phys. Rev. D **68** (2003) 054018; A. Bondar, Proceedings of BINP special analysis meeting on Dalitz analysis, 24-26 Sep. 2002, unpublished
- [13] J. Libby *et al.* [CLEO coll.], Phys. Rev. D **82** (2010) 112006.
- [14] R. Aaij *et al.*, [LHCb coll.], Phys. Lett. B **718** (2012) 43; R. Aaij *et al.*, [LHCb coll.], LHCb-CONF-2013-004, CERN-LHCb-CONF-2013-004.
- [15] K. De Bruyn *et al.*, Nucl. Phys. B **868** (2013) 351.
- [16] R. Aaij *et al.*, [LHCb coll.], arXiv:1407.6127 [hep-ex].
- [17] R. Aaij *et al.*, [LHCb coll.], Phys. Rev. Lett. **110** (2013) 10, 101802.
- [18] N. Lowrey *et al.* [CLEO coll.], Phys. Rev. D **80** (2009) 031105.
- [19] R. Aaij *et al.*, [LHCb coll.], Phys. Lett. B **726** (2013) 151; R. Aaij *et al.*, [LHCb coll.], LHCb-CONF-2013-006.
- [20] R. Aaij *et al.*, [LHCb coll.], LHCb-CONF-2014-004.
- [21] R. Aaij *et al.*, [LHCb coll.], arXiv:1407.8136 [hep-ex].
- [22] R. Aaij *et al.*, [LHCb coll.], Phys. Lett. B **733** (2014) 36.
- [23] R. Aaij *et al.*, [LHCb coll.], JHEP **1410** (2014) 97.
- [24] I. Bediaga *et al.*, [LHCb coll.], CERN-LHCC-2012-007.
- [25] R. Aaij *et al.*, [LHCb coll.], Phys. Rev. D **89** (2014) 3, 032001.
- [26] A. K. Giri, R. Mohanta and M. P. Khanna, Phys. Rev. D **65** (2002) 073029.